DIGITAL ELEVATION MAP PARAMETRIC ERROR ANALYSIS USING CORRESPONDING NAC IMAGES

Chris R. Gnam[1*], Carolina Restrepo[1], and Andrew L. Liounis[1]; [1]Goddard Space Flight Center (8800 Greenbelt Rd, Greenbelt, MD 20771) [*][christopher.gnam@nasa.gov]

Abstract. *Future lunar landing systems, particularly those used to land humans on the lunar surface as part of the ARTEMIS program, will require precision navigation relative to the lunar surface. The most common way to meet these stringent navigation requirements is through terrain relative navigation (TRN), which localizes a spacecraft by comparing descent imagery with a predefined map of the surface. The accuracy achievable using TRN is limited by the accuracy of the reference Digital Elevation Map (DEM). It is therefore critical for future lunar missions that potential errors in DEMs be quantified. This paper describes one of NASA's current efforts to develop a process for evaluating lunar DEM quality.*

Introduction. Precision Terrain Relative Navigation (TRN) is an enabling techonology for many upcoming missions, particularly those which aim to land humans on the lunar surface as part of the ARTEMIS program. The accuracy of such navigation is limited by the accuracy of the navigation maps which are used. Typically, these maps are constructed and stored as a digital elevation map (DEM), where each pixel of an image is used to store the height of a particular point on the surface relative to some datum, often a reference ellipsoid. Because of their use in navigation, minimizing errors in these DEMs and quantifying how any remaining errors may impact navigation performance is critical.

NASA's Lunar Navigation Maps project (LuNaMaps) was created to tackle both sides of this problem by leveraging the experience from previous missions which relied heavily on TRN such as Mars2020[1] and OSIRIS-REx.[2] In addition, it utilizes data from the Lunar Reconnaissance Orbiter (LRO) as well as expertise from the LRO instrument scientists. The goal is to both improve lunar DEM quality, and to quantify the impact of DEM errors on navigation performance.[3]

This paper addresses part of the LuNaMaps effort to characterize potential DEM errors in existing DEMs. We describe a framework whereby potential DEM errors are quantified by systematically deforming the DEMs and comparing how those deformations impact correlation performance between rendered templates of the DEM, and images captured by the LRO's Narrow Angle Camera (NAC).

Methodology. Previous analyses attempting to understand the bounds on errors in existing DEMs have looked at potential local errors, whereby the height of individual pixels on a DEM are modified and considered on their own. The pixel heights are adjusted up and down until the simulated illumination of the pixel varies by larger than a set amount from a flight NAC image that has been aligned with the DEM, giving an upper-bound on the potential height errors of a given pixel. While these sorts of error maps are useful, they do not capture the full breadth of potential error types that can exist in a DEM.

For our analysis, we study the effects of different deformations on the DEM in order to mimic potential errors in the DEM construction process. Some of these deformations are local (such as adjusting individual heights on the DEM image) allowing us to compare our results with previous works. Others are global (such as flattening/scaling the entire DEM). These sorts of larger scale errors are of more interest, as mapping techniques such as photoclinometry tend to produce the more global errors as opposed to individual pixel errors.[4] Specifically, we apply local deformations to the height and albedo of individual map pixels and the following global deformations:

- **scale**—multiply all height and DEM coordinate values by a constant to grow/shrink the map
- **smoothing**—smooth the heights across the DEM using a Gaussian kernel or similar
- **skew**—stretch the underlying DEM coordinates to elongate the DEM in various directions
- **shift**—globally shift the heights and DEM coordinate values by a constant
- **rotation**—rotate the DEM by a specified value
- **low frequency noise**—add slowly varying, continuous, local deformations to the DEM heights and coordinate values, so that local regions of the map experience similar deformations.

We note that though we base this list of deformations on previous experience, we are solely testing to put constraints on how much of each deformation is possible before it begins to be noticeable given the data we have available to us.

Once these deformations are applied, the DEM is rendered using a ray tracing algorithm. Analysis is primarily done using the Goddard Image Analysis and Navigation Tool (GIANT).[5] GIANT has been used for a number of projects including operationally for the OSIRIS-REx mission.[6] It provides an Application Programming Interface (API) for performing various rendering, image processing, and other navigation operations. Once the DEMs are rendered using the GIANT ray tracer, the rendered templates are compared with corresponding NAC images using correlation to quantify similarity.

The first step of the quality analysis of a specific DEM, is to identify which NAC images cover the DEM/region we are interested in. For this, the LROC QuickMap tool* is used to identify all of the NAC images which cover that same region. This tool also provides all of the associated SPICE kernels required for rendering the DEM with the same illumination and viewing conditions as the corresponding NAC image.

To properly render the images such that they can be compared directly to NAC images, a linear pushbroom camera model was implemented in GIANT. The NAC instruments found on the LRO are both Linear Pushbroom (LPB) sensors which means that they contain sensors with a single line of pixels.[7] These pixels are pointed towards the surface and all of the pixels are sampled repeatedly for a set period of time. Each sampling of the linear array of pixels corresponds to a single line in the final image, which is constructed as the camera flies over the planetary surface. An LPB model was implemented in GIANT, allowing for these types of images to be accurately simulated using the GIANT ray tracer. A diagram of the LPB model can be seen in Fig. 1.

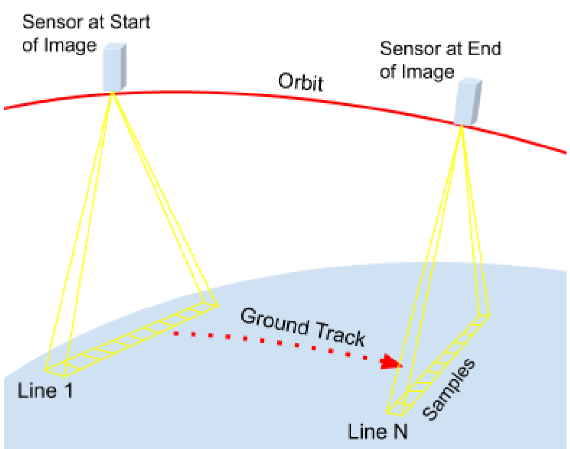

Figure 1. Linear Pushbroom Model (LPB)

The applied deformations are then be varied until the rendered image deviates from the true NAC image by some to-be-determined amount, at which point an upperbound on the potential error can be identified. This process is outlined in Fig. 2.

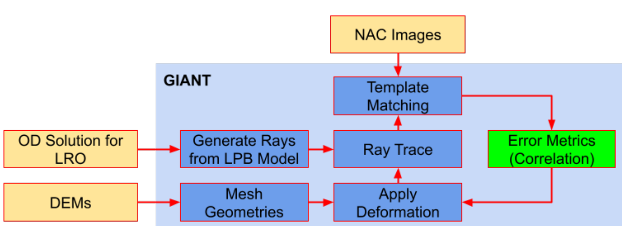

Figure 2. Flowchart of the NAC image comparison

*https://quickmap.lroc.asu.edu

Results. We produce error maps for different deformation types. These maps inform users what potential errors could exist in the corresponding DEM. This data will be validated with previous similar efforts to quantify DEM errors, and will be used for further analysis into how DEM errors impact navigation performance.

References.

[1] A. Johnson, S. Aaron, J. Chang, Y. Cheng, J. Montgomery, S. Mohan, S. Schroeder, B. Tweddle, N. Trawny, and J. Zheng, "The lander vision system for mars 2020 entry descent and landing," in *AAS Guidance and Control Conference*, 2017.

[2] D. A. Lorenz, R. Olds, A. May, C. Mario, M. E. Perry, E. E. Palmer, and M. Daly, "Lessons learned from osiris-rex autonomous navigation using natural feature tracking," in *2017 IEEE Aerospace Conference*, 2017.

[3] C. I. Restrepo, N. E. Petro, M. K. Barker, E. Mazarico, A. Liounis, C. Gnam, S. Scheidt, J. Richardson, A. I. Ansar, Y. Cheng, Z. Morgan, Y. Iwashita, and R. A. Beyer, "Building lunar maps for terrain relative navigation and hazard detection applications," in *AIAA SciTech Forum*, 01 2022.

[4] C. R. Gnam, A. J. Liounis, C. Adam, J. Leonard, P. Antreasian, D. S. Lauretta, and the OSIRIS-REx Team, "A novel surface feature navigation algorithm using ray tracing," in *2nd Annual RPI Workshop on Image-Based Modeling and Navigation for Space Applications*, 2019.

[5] A. J. Liounis, C. Gnam, J. Swenson, K. Getzandanner, J. Small, and J. Lyzhoft, "The Goddard Image Analysis and Navigation Tool," 1 2022. https://github.com/nasa/giant.

[6] A. J. Liounis, J. Swenson, J. Small, J. Lyzhoft, B. Ashman, K. Getzandanner, D. Highsmith, M. Moreau, C. Adam, P. Antreasian, D. Lauretta, and the OSIRIS-REx team, "Independent optical navigation processing for the osiris-rex mission using the goddard image analysis and navigation tool," in *2nd Annual RPI Workshop on Image-Based Modeling and Navigation for Space Applications*, 2019.

[7] R. Hartley and R. Gupta, "Linear pushbroom cameras," in *Third European Conference on Computer Vision*, vol. 800, pp. 555–566, 05 1994.